AN4398

Sensorless Field Oriented Control for a Permanent Magnet Synchronous Motor Using Sliding Mode Observer

Introduction

The Permanent Magnet Synchronous Motor (PMSM) is one of the preferred choices for motor control applications. Due to its permanent magnet rotor, it has higher torque with a smaller frame size and no rotor current, all of which are advantages over AC Induction Motors (ACIMs). With their high power-to-size ratio, PMSMs can help make the design smaller without the loss of torque. These strengths enable the usage of PMSMs in a broad range of variable frequency drive (VFD) applications.

Field Oriented Control (FOC) is the conventional choice for controlling the PMSM-based VFD. The FOC takes phase currents and the rotor flux angle of the three-phase AC motor as inputs, and generates a commutation pattern for a three-phase voltage source inverter, such that the resulting stator flux is at a specified angle to the rotor flux. This provides optimal torque and speed performance. The FOC essentially achieves this by transforming the three-phase components in the stator reference frame to two decoupled components in the rotor flux reference frame: one for controlling the overall flux in the motor and the other for controlling the torque.

The transformation from the stator reference frame to the rotor reference frame requires precise knowledge of the rotor flux angle. The rotor flux angle can be obtained by using either the appropriate position sensors (in sensored FOC), or by using the position estimators (in sensorless FOC). In sensorless FOC, the challenge is to implement a robust speed estimator that can reject perturbations, such as temperature, switching noise, electromagnetic noise, and so on. The sliding mode observer provides an excellent choice when it comes to a rotor position estimator under the presence of unknown signals and uncertainties.

Several documents from Microchip explain the principles behind FOC. An example is *AN2520 Sensorless Field Oriented Control (FOC) for a Permanent Magnet Synchronous Motor (PMSM) Using a PLL Estimator and Equation-based Flux Weakening (FW)* (see References).

This document covers the following topics:

- Permanent Magnet Synchronous Motor (PMSM)
- Field Oriented Control (FOC) principle
- Rotor position and speed estimation with a Sliding Mode Observer (SMO)
- Design and implementation of Sensorless FOC Example Software

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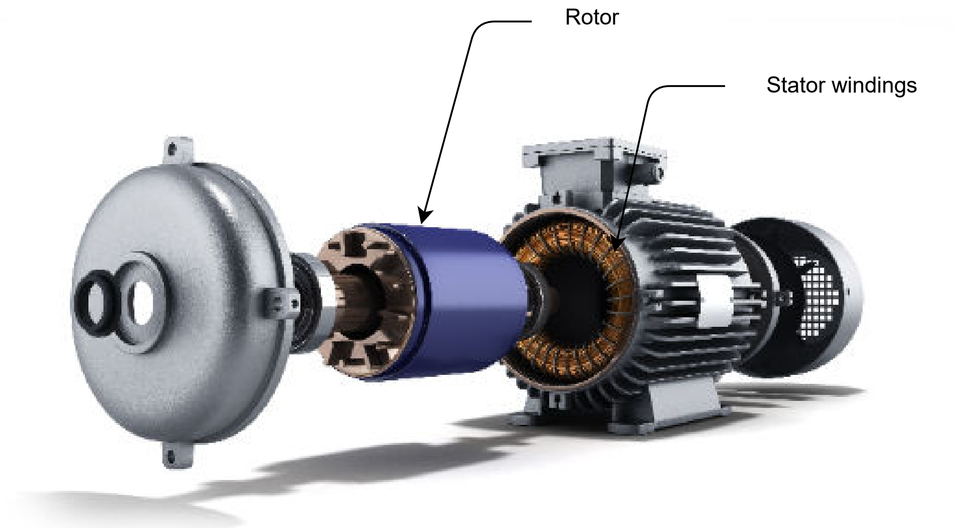
1. Permanent Magnet Synchronous Motors

The Permanent Magnet Synchronous Motor (PMSM) is an AC synchronous motor driven by a three-phase controlled AC supply. The following figure shows a split view of a typical PMSM.

Figure 1-1. Split View of a PMSM Motor



The PMSM has a stationary part called the stator, a rotating part called the rotor. The stator consists of three-phase windings. When the stator is excited with a balanced three-phase voltage, it generates a rotating magnetic field. The rotor has implanted permanent magnets on its core, which generates the rotor's magnetic field. The rotor's magnetic field interacts with the stator's rotating magnetic field to produce the rotor torque.

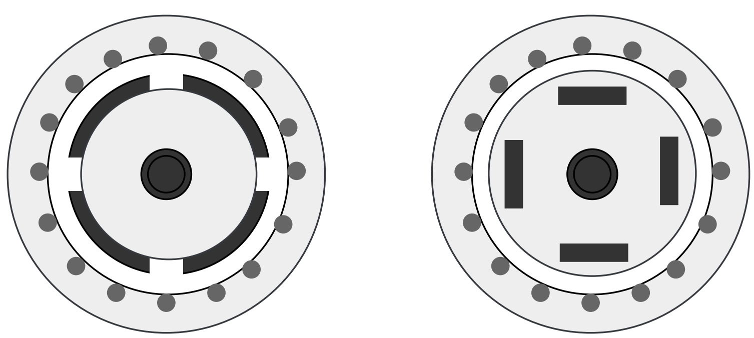
PMSMs are broadly classified into the following two categories depending upon the rotor construction:

- Surface-mounted PMSM (SPMSM)
- Interior-buried PMSM (IPMSM)

The SPMSM has the permanent magnets fixed on the surface of the rotor leading to a symmetrical radial air-gap reluctance path between the rotor and the stator core. The IPMSM has the permanent magnets inserted inside the rotor core leading to a non-symmetrical radial air-gap reluctance path between the rotor and the stator core.

The following figure shows the transversal-sectional view of SPMSM and IPMSM rotor configurations.

Figure 1-2. Rotor Transversal Section



(a). Surface-mounted rotor (b). Interior-buried rotor

1.1 Mathematical Model

The effective mathematical model of PMSM is critical for controller and observer design for PMSM-based Variable Frequency Drives (VFDs). Even though PMSMs are inherently non-linear systems, for most practical purposes, they can be approximated and modeled as a linear time-invariant dynamic system. The following section briefly introduces simple linear dynamic models of the PMSM in the stationary and rotational reference frame.

1.1.1 Stationary Reference Frame Model

The following equation represents the stationary model of PMSM:

Equation 1-1. Stationary Reference Frame Model

$$\begin{bmatrix} U_\alpha \\ U_\beta \end{bmatrix} = R_s \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} + p\mathbf{L}_{\alpha\beta} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} + \begin{bmatrix} e_\alpha \\ e_\beta \end{bmatrix}$$

Where:

- $\begin{bmatrix} U_\alpha \\ U_\beta \end{bmatrix}$ is the stator voltage in a stationary reference frame
- $\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}$ is the stator current in a stationary reference frame
- $\begin{bmatrix} e_\alpha \\ e_\beta \end{bmatrix}$ is the stator back EMF in a stationary reference frame
- R_s is the stator per phase resistance
- $p = d/dt$ is the differential operator

Equation 1-2. Inductance Matrix

$$\mathbf{L}_{\alpha\beta} = \begin{bmatrix} \frac{L_d + L_q}{2} + \frac{L_d - L_q}{2}\cos(2\theta_e) & \frac{L_d - L_q}{2}\sin(2\theta_e) \\ \frac{L_d - L_q}{2}\sin(2\theta_e) & \frac{L_d + L_q}{2} - \frac{L_d - L_q}{2}\cos(2\theta_e) \end{bmatrix}$$

- L_d is the inductance when the winding axis is aligned to the rotor flux axis
- L_q is the inductance when the winding axis is orthogonal to the rotor flux axis
- θ_e is the rotor flux angle

Equation 1-3. Back EMF

$$\begin{bmatrix} e_\alpha \\ e_\beta \end{bmatrix} = w_e \lambda_m \begin{bmatrix} -\sin(2\theta_e) \\ \cos(2\theta_e) \end{bmatrix}$$

- λ_m is the permanent magnet flux linkage
- w_e is the electrical speed of the motor

1.1.2 Rotational Reference Frame Model

The rotational reference frame model of the PMSM is derived by linear transformation of the PMSM equations from a stationary reference frame to a rotating reference frame (Park's Transformation). The transformation essentially converts all sinusoidally varying components to two DC components, thereby making control and analysis using classical control straightforward. The first component is aligned to the rotor flux (d-axis), while the second component is orthogonal to the rotor flux (q-axis). The step wise derivation of the model is beyond the scope of this document, and is therefore not discussed.

The following equation shows the final model in the rotational reference frame after the Park's transformation.

Equation 1-4. Rotational Reference Frame Model

$$\begin{bmatrix} U_d \\ U_q \end{bmatrix} = R_s \begin{bmatrix} I_d \\ I_q \end{bmatrix} + p\mathbf{L_{dq}} \begin{bmatrix} I_d \\ I_q \end{bmatrix} + \mathbf{J} w_e \mathbf{L_{dq}} \begin{bmatrix} I_d \\ I_q \end{bmatrix} + w_e \begin{bmatrix} 0 \\ \lambda_m \end{bmatrix}$$

Where:

- $\begin{bmatrix} U_d \\ U_q \end{bmatrix}$ is the stator phase voltage vector in a rotating reference frame
- $\begin{bmatrix} I_d \\ I_q \end{bmatrix}$ is the stator phase current vector in a rotating reference frame
- $\mathbf{J} = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$ is the rotational matrix

Equation 1-5. Inductance Matrix in Rotational Reference Frame

$$\mathbf{L_{dq}} = \begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix}$$

Where:

- L_d is the inductance along the d-axis
- L_q is the inductance along the q-axis

2. Field Oriented Control

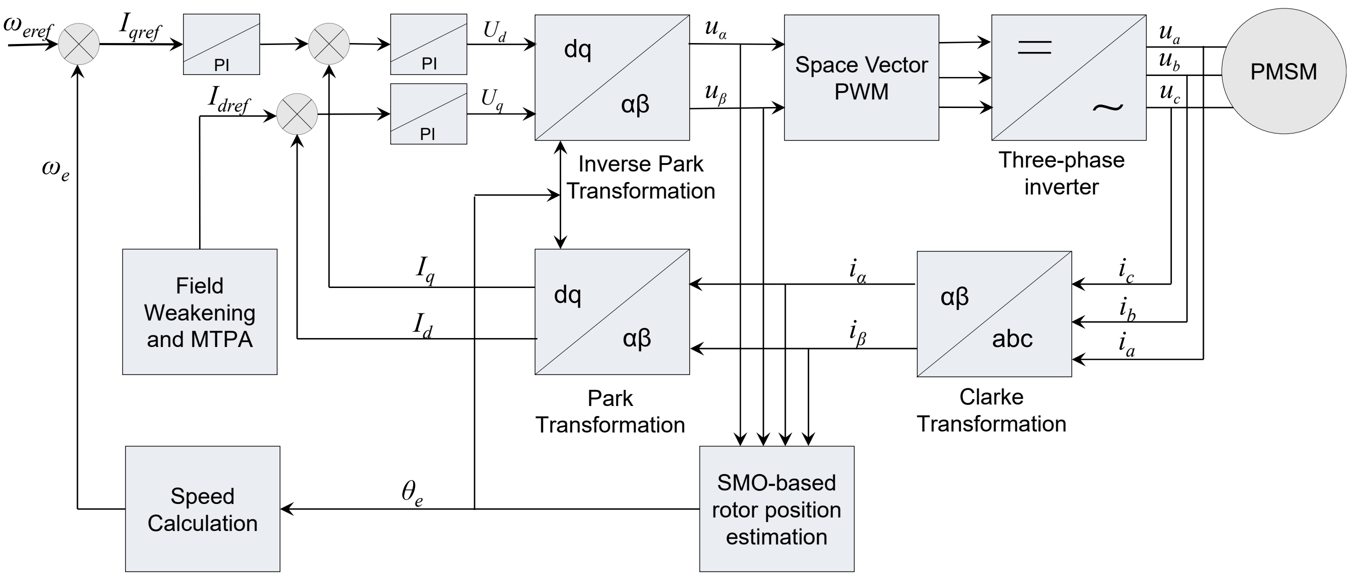
The Field Oriented Control (FOC) takes phase currents and the rotor magnetic field vector angle of the three-phase AC motor as inputs and generates a commutation pattern for a three-phase voltage source inverter. The resulting stator flux is at a specified angle to the rotor magnetic field vector, thereby providing optimal torque and speed performance.

The following section discusses the basic FOC scheme to control PMSM VFD.

2.1 FOC Based Variable Frequency PMSM Drive

The following figure shows a simple block diagram of a typical FOC-based PMSM variable frequency drive:

Figure 2-1. FOC Block Diagram



The following steps summarize the basic sensorless FOC operation:

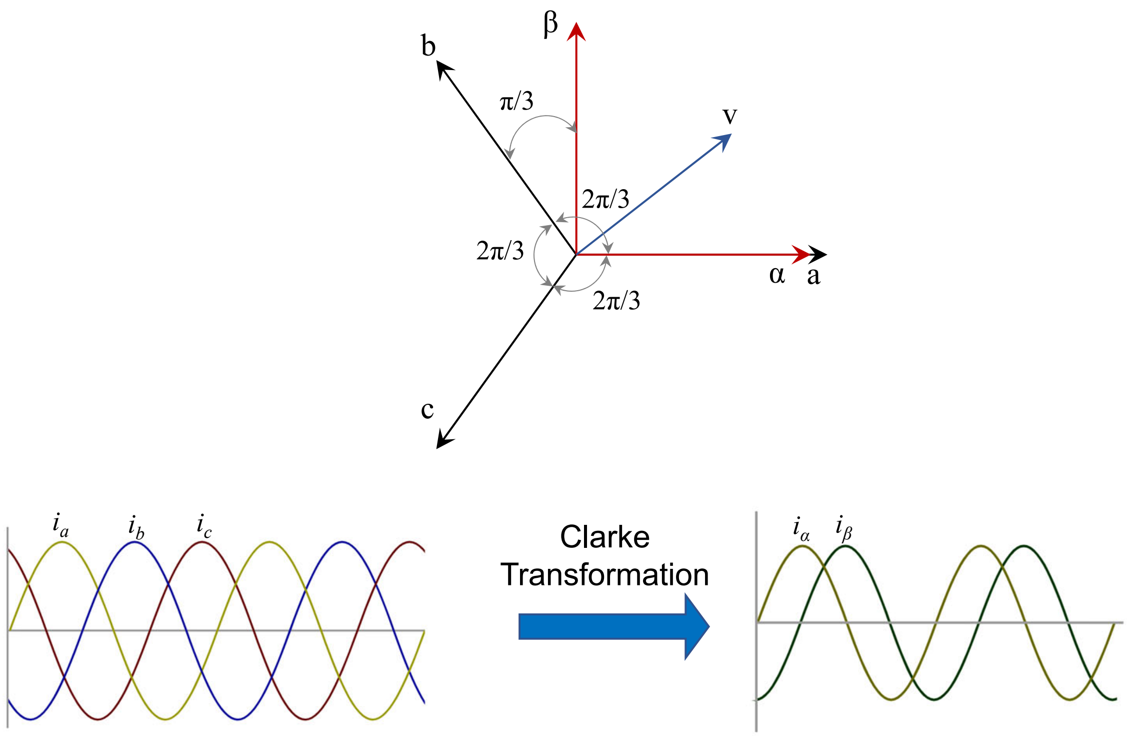
1. **Measure the current flowing in the motor:** There are several ways to measure the three-phase currents flowing in the motor. Some popular options include measurement using hall-effect, transformer-based magnetic sensors, or using strategically placed one, two or three shunt resistors.
2. **Estimate the rotor flux angle:** The rotor flux angle can be estimated either by back EMF-based algorithms or by high-frequency pulse injection.
3. **Transform the measured current to *αβ* reference frame:** The measured phase currents of the motor are transformed to two orthogonal components in the αβ reference frame by the Clarke Transformation.
4. **Transform the αβ current to *dq* current:** The *αβ* are transformed to two orthogonal components in the *dq* reference frame using the estimated rotor flux angle by the Park Transformation.
5. **Compare the measured *dq* current with the desired current and generate an error signal:** The desired q-axis reference current for controlling the torque, and desired d-axis current for controlling the flux are compared with their corresponding measured quantities to generate the respective error signals.
6. **Calculate control voltage from the error signal:** The error signals are used to calculate correction voltage. Conventionally a closed-loop feedback mechanism using a PI regulator is used for the task.
7. **Apply control voltage to motor terminals:** The correction voltage in the *dq* reference frame is transformed back to voltages in the *abc* reference frame. These voltages are applied to the motor terminals by some power switching techniques. Conventionally in MCU-based systems, PWM modulation techniques, such as Space Vector modulation are used for the task.

The following section describes various blocks of the FOC-based variable frequency drive in greater detail.

2.1.1 Clarke Transformation

The Clarke Transformation transforms the electrical signals from the three-axis reference frame (*abc*) to the two-axis orthogonal reference frame (*αβ*) as shown in the following figure.

Figure 2-2. Clarke Transformation



The transform is expressed by the following equations:

$$i_a + i_b + i_c = 0$$

$$i_\alpha = i_a$$

$$i_\beta = \frac{1}{\sqrt{3}}\left(i_b - i_c\right)$$

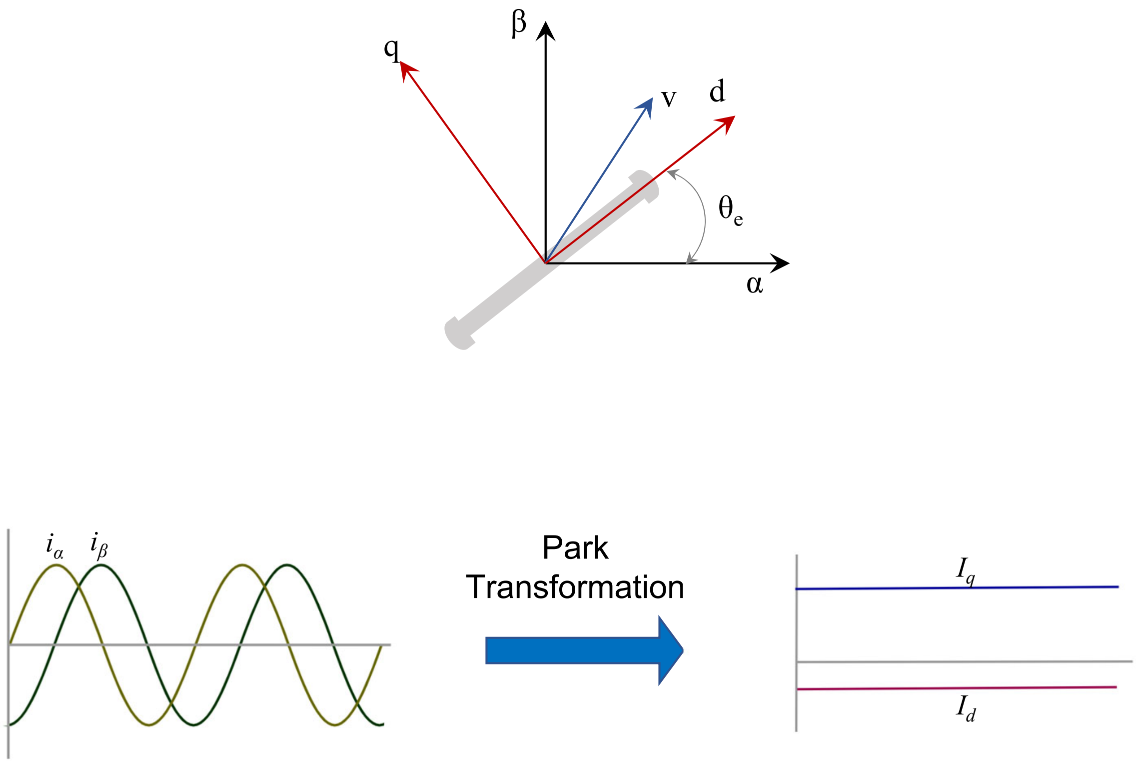
Where:

i_α, i_b and i_c are the three-phase currents in *abc* reference frame, i_α and i_β are the two-phase orthogonal currents in the *αβ* reference frame.

2.1.2 Park Transformation

The Park Transformation transforms electrical signals from the two-axis orthogonal stationary reference frame (*αβ*) to the two-axis orthogonal rotating reference frame (*dq*) as shown in the following figure.

Figure 2-3. Park Transformation



The transform is expressed by the following equations:

$$I_d = i_\alpha \cos\theta + i_\beta \sin\theta$$

$$I_q = -i_\alpha \sin\theta + i_\beta \cos\theta$$

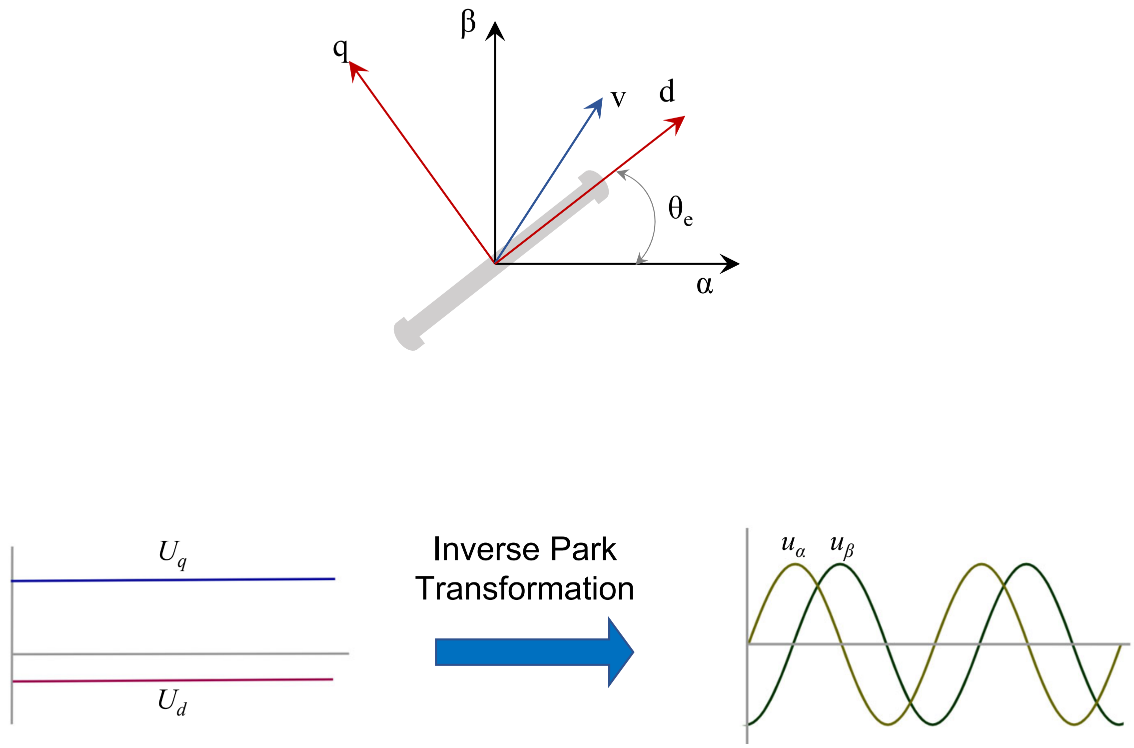
Where:

i_α and i_β are currents in two-axis orthogonal *αβ* reference frame,I_d and I_q are currents in the two-axis orthogonal *dq* rotating reference frame.

2.1.3 Inverse Park Transformation

The Inverse Park Transformation transforms electrical signals from the rotating two-axis orthogonal reference frame (*dq*) to the two-axis orthogonal stationary reference frame (*αβ*) as shown in the following figure.

Figure 2-4. Inverse Park Transformation



The transform is expressed by the following equations:

$$u_\alpha = U_d\cos(\theta_e) - U_q\sin(\theta_e)$$

$$u_\beta = U_d\sin(\theta_e) + U_q\cos(\theta_e)$$

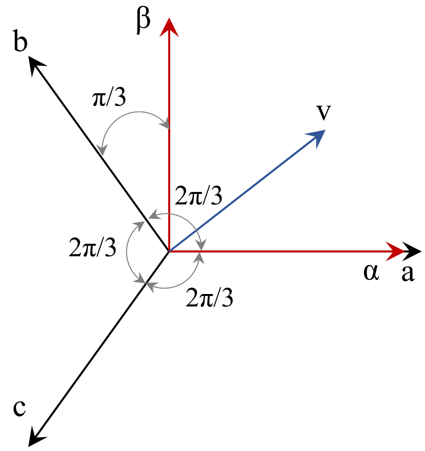
Where:

U_d and U_q are voltages in the two-axis orthogonal *dq* rotating reference frame, and U_α and U_β are voltages in the two-axis orthogonal αβ reference frame.

2.1.4 Inverse Clarke Transformation

The Inverse Clarke Transformation transforms electrical signals from the stationary two axis orthogonal reference frame (*αβ*) to the three axis reference frame (*abc*) as shown in the following figure.

Figure 2-5. Inverse Clarke Transformation



The transform is expressed by the following equations:

$$U_a = U_\alpha$$

$$U_b = -\frac{1}{2}U_\alpha + \frac{\sqrt{3}}{2}U_\beta$$

$$U_c = -\frac{1}{2}U_\alpha - \frac{\sqrt{3}}{2}U_\beta$$

Where:

U_α and U_β are the two-phase orthogonal voltages in the *αβ* reference frame, U_a, U_b, and U_c are the three-phase voltages in the *abc* reference frame.

2.1.5 Proportional Integral Controller

A Proportional Integral (PI) controller is the most widely used algorithm for motor control applications. Although it may not be the most optimum controller for all applications, it is easy to understand and tune. The following equation describes a traditional PI controller:

Equation 2-1. Tracking Error

$$e(t) = r(t) - y(t)$$

Equation 2-2. PI Controller

$$u(t) = K_p e(t) + K_i \int e(t)dt$$

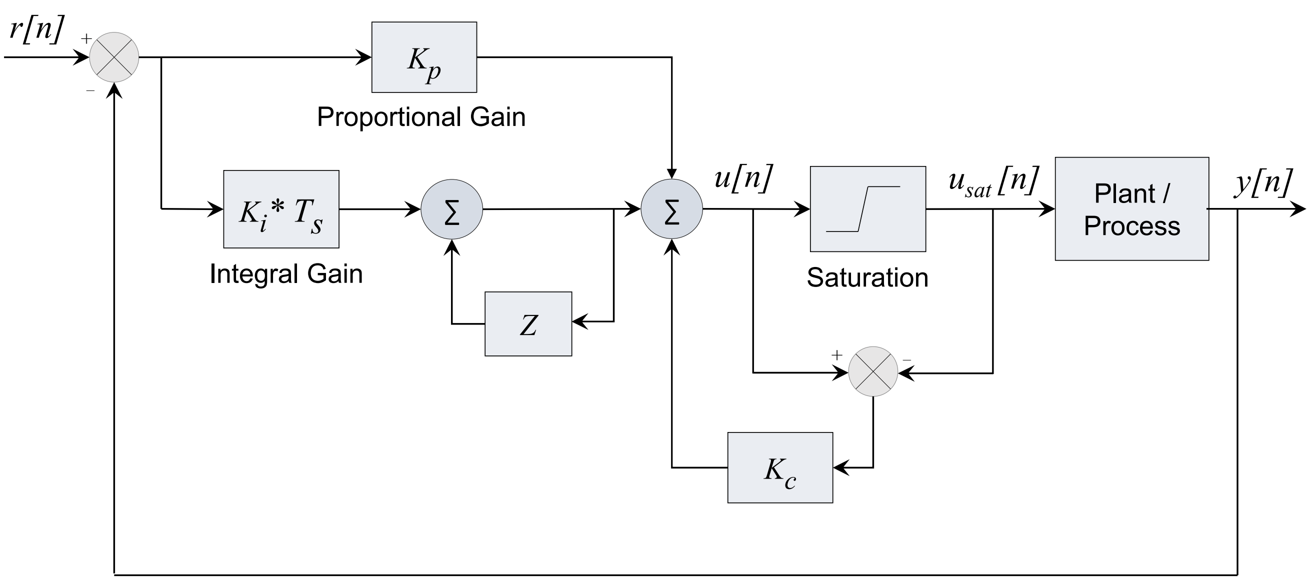
Where:

- *r(t)* and *y(t)* are reference and actual process/plant signals
- K_p,K_i are the proportional and integral gain

Practical PI controllers face the problem of integrator windup. Integrator windup is a condition that occurs when a large ensuing error is present in the plant or process. The integrator continually builds up during this following error condition even though the output is saturated. The integrator then unwinds when the plant reaches its final value causing excessive oscillation. To avoid accumulation of integrators when the output saturates, anti-windup techniques are used.

The following figure shows a PI controller with back calculation based anti-windup:

Figure 2-6. Discrete PI Controller



2.1.6 Space Vector Pulse Width Modulation

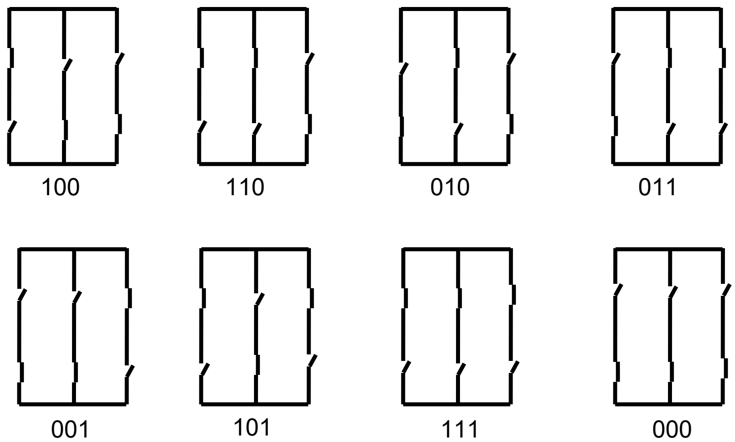
The Space Vector Pulse Width Modulation (SVPWM) is a conventional technique to drive a two-level voltage source inverter. It provides the following advantages:

- It improves the harmonic content of the phase voltages
- It increases the DC bus utilization range by about 15%

The following section describes the theory behind the SVPWM.

Each of the inverter phase outputs can be in any one of the two states: zero when it is connected to the negative rail, and one when it is connected to the positive rail. Therefore, a three-phase inverter can have 2^3 = 8 possible states as shown in the following figure.

Figure 2-7. Space Vector Modulation



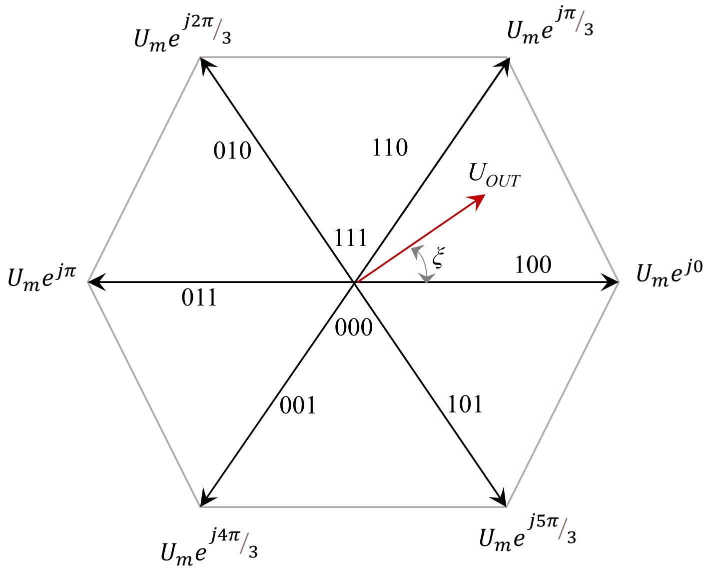
Each state represents a space vector with a magnitude and phase angle as provided in the following table:

Table 2-1. Magnitude and Phase Angle

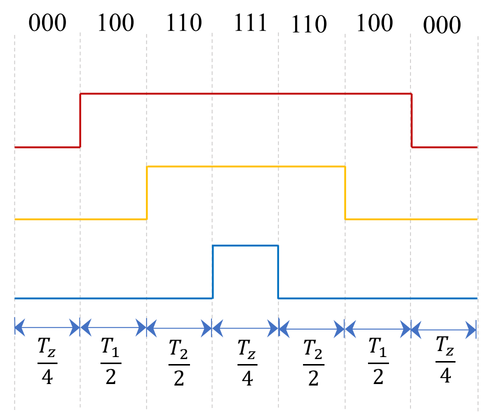
Index	State	Space Vector
0	000	0
1	100	$U_m e^{j0}$
2	110	$U_m e^{j\pi/3}$
3	010	$U_m e^{j2\pi/3}$
4	011	$U_m e^{j\pi}$
5	001	$U_m e^{j4\pi/3}$
6	101	$U_m e^{j5\pi/3}$
7	111	0

The states with index zero and seven are null states, because there is no line-to-line voltage across any of the phases in these states. All the states other than the null states are active states and represent a phase with a magnitude, and a phase in the space vector plane. The following figure shows these space vectors.

Figure 2-8. Space Vector Modulation



a. Space Vectors for inverter states



b. PWM signals generation for U_{OUT}

The SVPWM technique generates any space vector with a specified magnitude and angle by modulating between the two adjacent active vectors, between which the desired vector lies and the null vectors. The transitions between different states are carried out, hence only one power switch transition happens between state transition.

Equation 2-3. Desired Space Vector Calculation

$$U_{OUT} = \frac{1}{T_s}\left(T_k U_m e^{jk\pi/3} + T_l U_m e^{jl\pi/3} + \frac{T_z}{2}U_0 + \frac{T_z}{2}U_7\right)$$

$$T_s = T_k + T_l + T_z$$

Where:

- U_m is the maximum AC peak voltage
- T_s is the PWM period
- T_k and T_l are the time for which adjacent active vectors are imposed
- U_0 and U_7 are null vectors for zero and seven states respectively
- T_z is the time for which the null vectors are imposed

3. Rotor Position and Speed Estimation

The accurate value of the rotor position is crucial for independent control of the PMSM torque and flux. The rotor position can be obtained either by using dedicated rotor position sensors (sensored techniques), or by using position estimators (sensorless techniques).

The sensorless technique based on the back-EMF signals is a popular class of sensorless techniques. The observer takes the phase currents and voltages as input, then determines the rotor back-EMF of the PMSM. The back-EMF in turn is used to calculate the rotor position. One major drawback of these techniques is that it requires a minimum value of back-EMF to estimate the electrical position of the rotor. Therefore, these techniques require an open loop start-up procedure to start the motor before executing FOC.

The following section describes a simple open loop start-up procedure, followed by a back-EMF based angle and speed estimation technique with a Sliding Mode Observer.

3.1 Start Up Procedure

The sensorless position estimation techniques based on back-EMF require a minimum value of back-EMF to estimate the electrical position of the rotor. The open-loop start-up procedure drives the PMSM till its speed reaches the minimum value where the back-EMF values are large enough to estimate the rotor position.

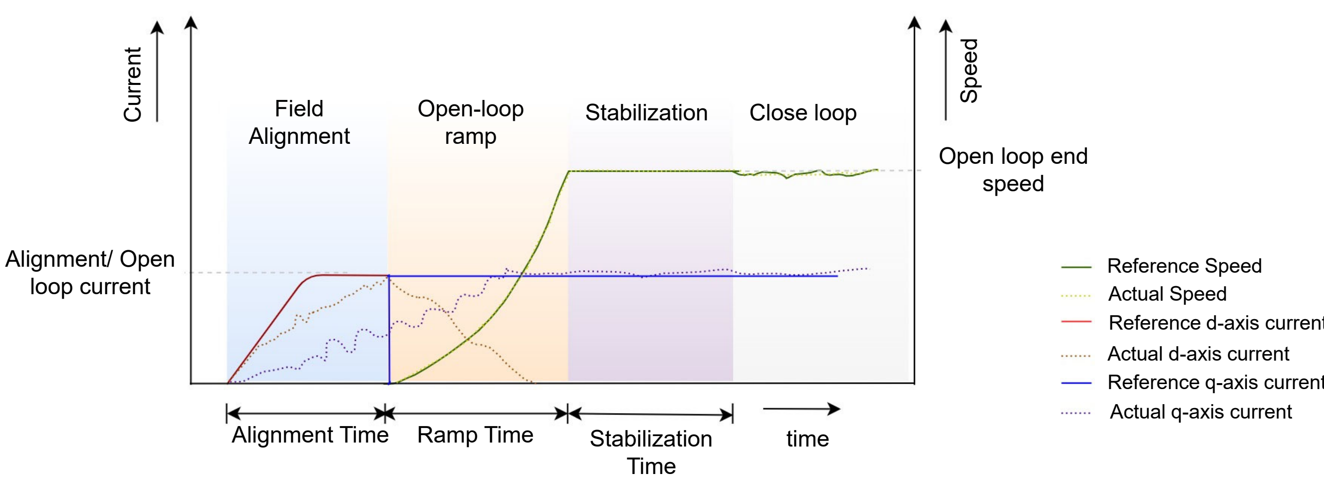
In the open-loop start-up procedure, the speed loop is deactivated. The current is controlled directly in the *dq* reference frame by using the assumed rotor position angles for the transformations.

The complete start-up procedure can be divided into the following phases:

- **Initial Field Alignment:** In this phase, the PMSM rotor is locked to a specified rotor position by applying a DC current in the stator phase windings. There are two methods by which this can be achieved: d-axis alignment and q-axis alignment. The following figure shows d-axis alignment, where the d-axis current is gradually ramped to a specified value at a fixed rotor position angle.
- **Open-loop Ramp:** In this phase, the rotor position is constantly incremented based on the user-defined ramp time at a specified q-axis current to achieve the minimum required speed for the BEMF observer. The minimum ramp time and speed depend on the PMSM drive's electrical and mechanical parameters. For a reliable start-up, proper tuning of the ramp time and reference current is needed.
- **Stabilization:** In this phase, the PMSM is allowed to rotate at a constant open-loop speed. This step ensures a smooth transition to close loop mode.

The complete start-up procedure is shown in the following figure:

Figure 3-1. Open-Loop Start-Up Procedure

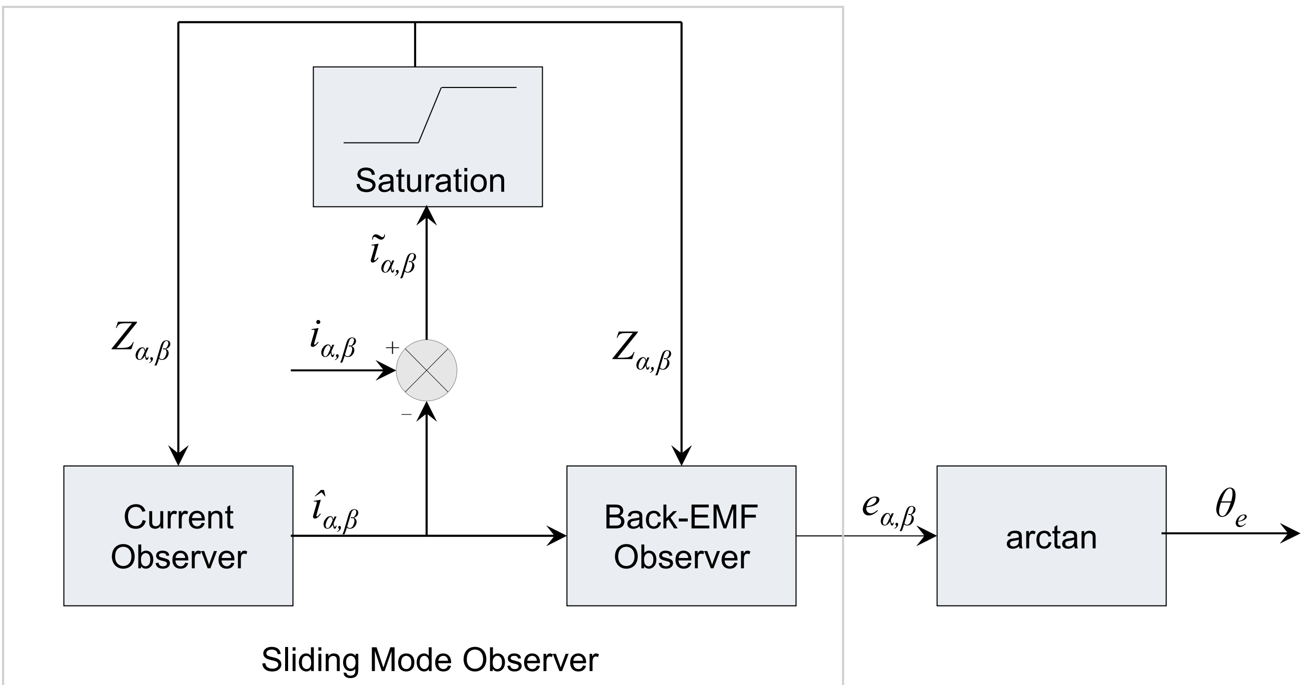


3.2 Sliding Mode Observer

The Sliding Mode Observers (SMO) belong to a class of non-linear observers used to estimate the internal state of an observable system based on the measured input and output. In this application, the SMO is used to estimate the back-EMFs of the PMSM. The major advantage of using SMO over a conventional linear back-EMF based rotor position and speed estimation is its robustness in the presence of unknown signals and uncertainties.

The SMO estimates the BEMFs using a PMSM system model, voltage, and current vector input. The following figure shows a simplified block diagram of the SMO-based rotor position and speed estimation method.

Figure 3-2. Sliding Mode Observer Based Angle Calculation



The following set of equations represent the state space model of a PMSM motor:

Equation 3-1. Current State Space

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}' = -\frac{R_s}{L_s}\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} - \frac{1}{L_s}\begin{bmatrix} e_\alpha \\ e_\beta \end{bmatrix} + \frac{1}{L_s}\begin{bmatrix} U_\alpha \\ U_\beta \end{bmatrix}$$

Equation 3-2. Back-EMF State Space

$$\begin{bmatrix} e_\alpha \\ e_\beta \end{bmatrix}' = w_e\mathbf{J}\begin{bmatrix} e_\alpha \\ e_\beta \end{bmatrix}$$

The observer can be expressed as follows:

Equation 3-3. Sliding Mode Current Observer

$$\begin{bmatrix} \hat{i}_\alpha \\ \hat{i}_\beta \end{bmatrix}' = -\frac{R_s}{L_s}\begin{bmatrix} \hat{i}_\alpha \\ \hat{i}_\beta \end{bmatrix} - \frac{1}{L_s}\begin{bmatrix} \hat{e}_\alpha \\ \hat{e}_\beta \end{bmatrix} + \frac{1}{L_s}\begin{bmatrix} \hat{U}_\alpha \\ \hat{U}_\beta \end{bmatrix} + \begin{bmatrix} \sigma(i_\alpha - \hat{i}_\alpha) \\ \sigma(i_\beta - \hat{i}_\beta) \end{bmatrix}$$

Equation 3-4. Back-EMF Observer

$$\begin{bmatrix} \hat{e}_\alpha \\ \hat{e}_\beta \end{bmatrix}' = w_e\mathbf{J}\begin{bmatrix} \hat{e}_\alpha \\ \hat{e}_\beta \end{bmatrix} - \mathbf{L}\begin{bmatrix} \sigma(i_\alpha - \hat{i}_\alpha) \\ \sigma(i_\beta - \hat{i}_\beta) \end{bmatrix}$$

Where:

- σ is the sliding function, and ***L*** is the back-EMF observer pole placement matrix

From the equations, the estimation error can be expressed as follows:

Equation 3-5. Current Estimation Error Dynamics

$$\begin{bmatrix}\tilde{i}_\alpha \\ \tilde{i}_\beta\end{bmatrix}' = -\frac{R_S}{L_S}\begin{bmatrix}\tilde{i}_\alpha \\ \tilde{i}_\beta\end{bmatrix} - \frac{1}{L_S}\begin{bmatrix}\tilde{e}_\alpha \\ \tilde{e}_\beta\end{bmatrix} - \begin{bmatrix}\sigma\left(i_\alpha - \hat{i}_\alpha\right) \\ \sigma\left(i_\beta - \hat{i}_\beta\right)\end{bmatrix}$$

Equation 3-6. Back-EMF Estimation Error Dynamics

$$\begin{bmatrix}\tilde{e}_\alpha \\ \tilde{e}_\beta\end{bmatrix}' = w_e\mathbf{J}\begin{bmatrix}\tilde{e}_\alpha \\ \tilde{e}_\beta\end{bmatrix} + \mathbf{L}\begin{bmatrix}\sigma\left(i_\alpha - \hat{i}_\alpha\right) \\ \sigma\left(i_\beta - \hat{i}_\beta\right)\end{bmatrix}$$

Where:

- $\begin{bmatrix}\tilde{i}_\alpha \\ \tilde{i}_\beta\end{bmatrix} = \begin{bmatrix}i_\alpha - \hat{i}_\alpha \\ i_\beta - \hat{i}_\beta\end{bmatrix}$ is the current estimation error
- $\begin{bmatrix}\tilde{e}_\alpha \\ \tilde{e}_\beta\end{bmatrix} = \begin{bmatrix}e_\alpha - \hat{e}_\alpha \\ e_\beta - \hat{e}_\beta\end{bmatrix}$ is the back-EMF estimation error

The sliding function σ is designed to be a discontinuous function of estimation errors such that the sliding condition is assured, and the system state is forced to zero in finite time. In this document, the following sliding mode function is used:

Equation 3-7. Sliding Mode Function

$$\sigma(x) = \begin{cases}\frac{mx}{\varphi} \;\; if \;\; |x| < \varphi \\ m, \;\; if \;\; x \geq \varphi \\ -m \;\; if \;\; x \leq -\varphi\end{cases}$$

If the value of *m* in the sliding mode function is large enough, a sliding condition is achieved and therefore the error dynamics evolves to zero. This implies:

$$\begin{bmatrix}\sigma\left(i_\alpha - \hat{i}_\alpha\right) \\ \sigma\left(i_\beta - \hat{i}_\beta\right)\end{bmatrix} \to -\frac{1}{L_S}\begin{bmatrix}\tilde{e}_\alpha \\ \tilde{e}_\beta\end{bmatrix}$$

Therefore, from the equations, the error dynamics of back-EMF observer can be expressed as:

Equation 3-8. Back-EMF Observer After Sliding Condition is Achieved

$$\begin{bmatrix}\tilde{e}_\alpha \\ \tilde{e}_\beta\end{bmatrix}' = \left(w_e\mathbf{J} - \frac{1}{L_S}\mathbf{L}\right)\begin{bmatrix}\tilde{e}_\alpha \\ \tilde{e}_\beta\end{bmatrix}$$

For a stable back-EMF observer, the matrix $\left(w_e\mathbf{J} - \frac{1}{L_S}\mathbf{L}\right)$ should have negative eigenvalues. In other words, for an eigenvalue of λ, the matrix ***L*** can be determined as follows:

$$w_e\mathbf{J} - \frac{1}{L_S}\mathbf{L} = \lambda\mathbf{I}$$

or,

Equation 3-9. Back-EMF Observer Pole Placement Matrix

$$\mathbf{L} = -L_S(\lambda\mathbf{I} - w_e\mathbf{J})$$

3.3 Rotor Angle Calculation

The rotor position is calculated from the observed back-EMF using following relation:

$$\theta_e = \tan^{-1}\left(e_\beta / e_\alpha\right) - sign\left(w_e\right)\pi/2$$

Where:

- sign (ωe) equals to the sign to the speed (ωe)

3.4 Rotor Speed Calculation

The rotor speed can be calculated by using the observed rotor position value. The incremental change in the rotor position angle is used to calculate the speed in a moving average filter.

$$\theta_e(n) = \frac{1}{NT_s}\left[\Delta\theta_e(n) + \Delta\theta_e(n-1) + \dots + \Delta\theta_e(n-N+1)\right]$$

Where:

N is the number of samples in a moving average filter, T_s is the sampling time, and $\Delta\Theta_e$ is the incremental change in the electrical rotor position.

The calculated rotor speed is further filtered using a Low Pass Filter (LPF) with a cut-off frequency Θ_c to avoid unwanted disturbances which could affect the result. The LPF can be implemented in discrete time with a sampling time T_s as follows:

$$\theta_{eFilt}(n) = (1 - \theta_c T_s)\theta_{eFilt}(n-1) + \theta_c T_s \theta_e(n)$$

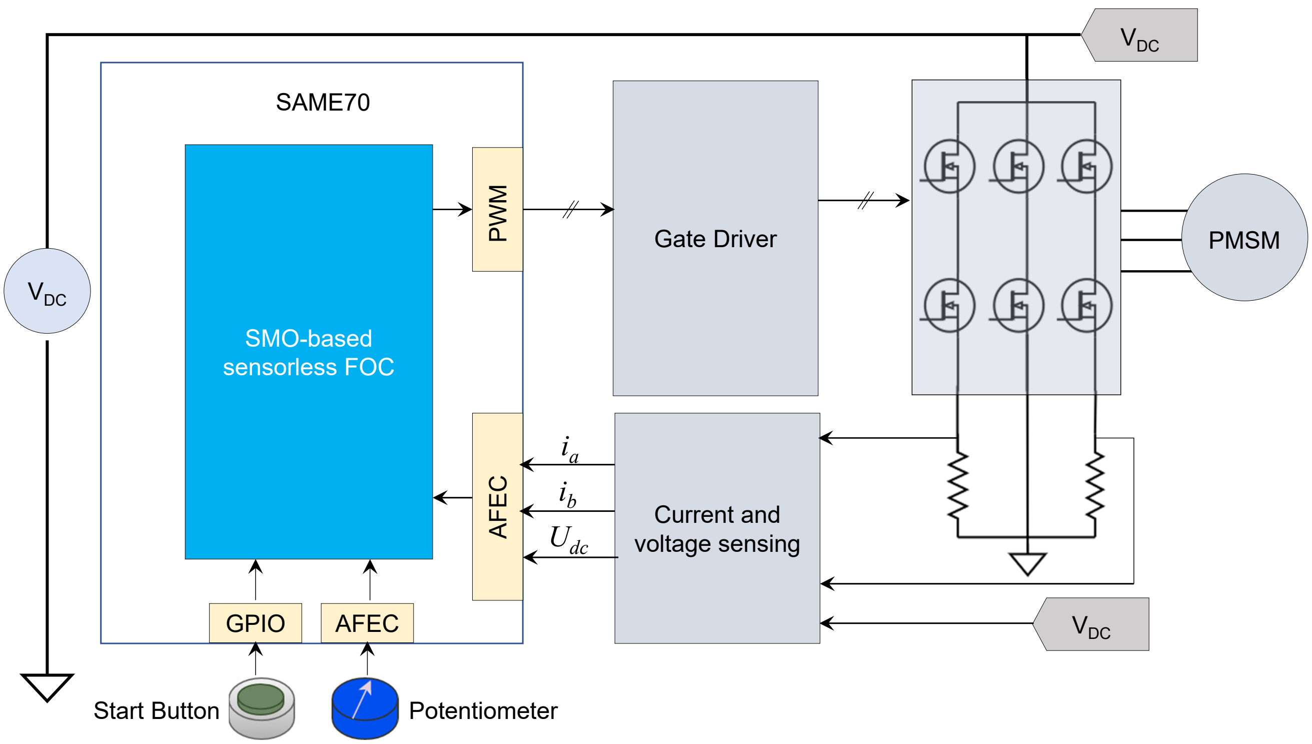
4. Field Oriented Control (FOC) Implementation

Microchip provides a broad range of 32-bit microcontrollers to cater to an extensive range of applications making them popular choices for Motor control applications. For more details on Microchip's 32-bit motor control MCU portfolio, refer to the Appendix.

This section provides a high-level overview of the SMO-based sensorless FOC implementation details using Microchip's SAME70 MCU as an example. The implementation details hold for other Microchip's 32-bit MCUs as well.

The following figure shows a simplified system-level diagram of the SMO based sensorless FOC PMSM drive:

Figure 4-1. System-Level Diagram of SMO Based Sensorless FOC PMSM Drive



4.1 SAME70 MCU Features and Peripheral Settings

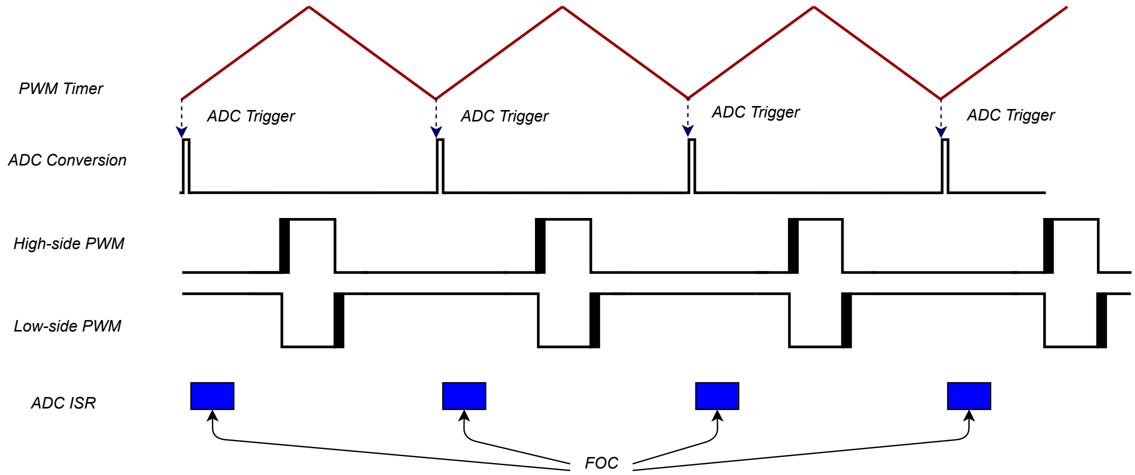
The SAME70 microcontrollers combine a 300 MHz Arm Cortex-M7 Core with up to 64 KB of tightly coupled core memory for a fast FOC, with up to two MB of Flash memory for creating high-performance applications. It features a pair of dual Sample-and-Hold (S/H) 12-bit ADC engines sampling at up to two MS/s in 12-bit mode, and up to eight PWM channels capable of generating complementary PWM with dead-time in Edge or center-aligned modes. For more information, refer to the SAME7x data sheet.

4.1.1 Hardware Timing and Synchronization

Field-oriented control requires accurate and precise timings to perform hardware and software functions for optimal motor control performance. The motor control dedicated peripherals of the SAME70 MCU enables handling of these timing requirements at the hardware level with minimal user settings.

The following figure illustrates the implementation of hardware timing and synchronization.

Figure 4-2. Hardware Timing and Synchronization



The PWM peripheral of the microcontroller in addition to generating the three phase PWM signals, triggers the ADC channels periodically on period match event. The triggered ADC channels take phase current A and phase current B as inputs and convert the signals to their digital equivalent for use by the software. Simultaneous samples of the phase currents are taken for optimal performance. In addition to phase currents, the software also measures the DC bus voltage. After the ADC conversion of the phase currents is completed, an interrupt is generated. The generated interrupt is used to carry-out start-up and subsequent FOC tasks. The calculated PWM cycles are updated in the PWM module to actuate the motor.

4.1.2 Motor Control Key Peripherals Usage

4.1.2.1 AFEC Peripheral

The AFEC (ADC) is used to measure analog quantities. Four channels are used to measure Phase Current A, Phase Current B, DC Bus Voltage, and the potentiometer reading. A conversion is triggered at the PWM (zero match + offset of the switch delay).

4.1.2.2 PWM Peripheral

This peripheral is used to generate three pairs of complementary PWM signals. Fault functionality is also enabled to switch off the output waveforms asynchronously.

4.1.3 Software Architecture

The software performs the following tasks:

- Microcontroller and motor control peripheral initialization
- FOC State machine in the ADC ISR
- Motor start and stop command through the GPIO button
- Motor speed command from the potentiometer

4.1.3.1 Motor Control Peripheral Initialization

On Power-on Reset (POR), the software initializes the microcontroller and motor control peripherals according to the user requirements.

4.1.3.2 Motor Control State Machine

The software implements the motor control tasks in the ADC ISR. The ADC ISR incorporates the following states:

- **Idle:** In this state, the motor does not spin. The software waits for a valid button press from the user to start the motor.
- **Start-up:** In this state, the software executes the PMSM start-up procedure as described in Start-Up Procedure.
- **Close-loop speed control:** In this state, the software executes an SMO-based sensorless FOC.

4.1.3.3 Motor Speed Command From Pentiometer

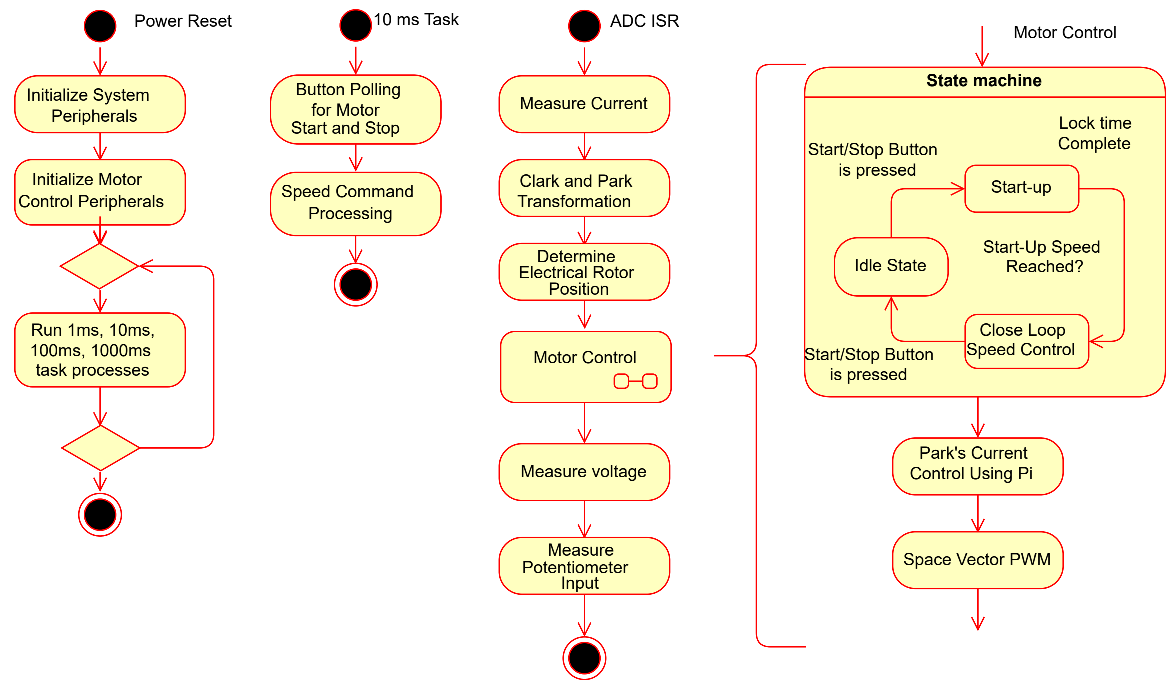
The software calculates the speed reference from the measured potentiometer input.

4.1.3.4 Motor Start and Stop Command by GPIO

The software polls the GPIO button every 10 ms to check if the button has been pressed. If the button press is detected, the software changes the motor control state from Idle to Start-up. This initiates the motor spin at the specified reference speed.

The following figure illustrates the software flow-chart of the example project:

Figure 4-3. Software Flow Chart



5. Conclusion

The document describes the speed control application of PMSMs by sliding mode observer based field-oriented control.

The theoretical ideas behind the linear PMSM models, field-oriented control, start-up procedure, sliding mode observer-based position, and speed estimation are described. Finally, the document describes the software implementation of the application using Microchip's SAME70 MCU as an example.

Using the SAME70 MCU and motor control software offered by Microchip, the customer can significantly shorten the time-to-market.

6. Appendix: Architectural Highlights of 32-bit MCUs for Motor Control Applications

The following sections list Microchip's 32-bit MCU portfolio with key features for motor control applications. For additional information, refer to the respective device data sheet.

6.1 PIC32CM MC Family

Key Features

- 48 MHz Arm® Cortex®- M0+ based MCUs with Up to 128 KB Flash
- Up to 1 Msps ADC
- Dual 12-bit ADCs and 10-bit DAC
- Motor Control PWM
- Positional Decoder (PDEC) for Motor Control
- Analog Comparators
- 16-bit Sigma-Delta ADC (SDADC)
- Operating Voltage: 2.7V to 5.5V
- Divide and Square Root Accelerator (DIVAS)
- Timer/Counter for Control (TCC) Peripheral Provides Dedicated Timers for Industrial and Motor Control

6.2 SAM D2x and C2x Families

Key Features

- 48 MHz Arm Cortex-M0+ based MCUs with Up to 256 KB Flash
- Up to 1 Msps ADC
- 12-bit DAC
- Motor control PWM
- Analog comparators
- CAN FD
- Sigma-delta ADC
- 5V devices

6.3 SAM D5x and SAM E5x Family

Key Features

- 120 MHz Arm Cortex-M4 based MCUs with Up to 1 MB Flash
- Up to 1 Msps ADC
- Motor Control PWM
- 12-bit DAC
- Analog comparators
- CAN FD
- Position Encoder Interface
- USB
- Ethernet

6.4 PIC32MK Family

Key Features

- 120 MHz MIPS® Core with Up to one MB of Dual-Panel Live Update Flash with ECC
- Seven 12-bit ADCs: 3.75 Msps; 25.45 Msps Combined Motor Control PWM
- Up to three 12-bit DACs
- Five analog comparators
- Up to four CAN FD
- Quadrature Encoder Interface (QEI)
- Up to two Full-Speed USB
- Four high-bandwidth Op Amps
- Single-Precision and Double-Precision Floating Point Unit (FPU) and DSP Extension Support

6.5 SAM S70 and SAM E70 Family

Key Features

- 300 MHz Arm Cortex-M7 based MCUs with Up to two MB Flash
- Up to 2 Msps ADC
- Motor Control PWM
- 12-bit DAC
- Analog comparators
- CAN FD
- Position Encoder Interface
- USB
- Ethernet
- Tightly Coupled Memory

7. References

- Speed Estimators, Flux Weakening and Efficient Use of SPMSM and IPMSM, 20089 MC7, Microchip MASTERs Conference 2016
- The following documents, are available for download from the Microchip web site (www.microchip.com):
  – PIC32CM MC00 Family Data Sheet (DS60001638): ww1.microchip.com/downloads/en/DeviceDoc/PIC32CM-MC00-Family-Data-Sheet-DS60001638D.pdf
  – SAM C20/C21 Family Data Sheet (DS60001479): ww1.microchip.com/downloads/en/DeviceDoc/SAM-C20-C21-Family-Data-Sheet-DS60001479H.pdf
  – SAM D20 Family Data Sheet (DS60001504E): ww1.microchip.com/downloads/en/DeviceDoc/SAM-D20-Family-Data-Sheet-DS60001504E.pdf
  – SAM D21/DA1 Family Data Sheet (DS40001882H): ww1.microchip.com/downloads/en/DeviceDoc/SAM-D21-DA1-Family-Data-Sheet-DS40001882H.pdf
  – SAM D5x/E5x Family Data Sheet (DS60001507G): ww1.microchip.com/downloads/en/DeviceDoc/SAM_D5x_E5x_Family_Data_Sheet_DS60001507G.pdf
  – PIC32MK General Purpose and Motor Control (GP/MC) Family Data Sheet (DS60001402G): ww1.microchip.com/downloads/en/DeviceDoc/PIC32MK_GP_MC_Familly_Datasheet_60001402G.pdf
  – SAM E70/S70/V70/V71 Family Data Sheet (DS60001527E): ww1.microchip.com/downloads/en/DeviceDoc/SAM-E70-S70-V70-V71-Family-Data-Sheet-DS60001527E.pdf
  – AN2520 Sensorless Field Oriented Control (FOC) for a Permanent Magnet Synchronous Motor (PMSM) Using a PLL Estimator and Equation-based Flux Weakening (FW) (DS:00002520C): ww1.microchip.com/downloads/en/AppNotes/Sensorless-FOC-For-PMSM-using-PLL-Estimator-FW-AN-DS00002520C.pdf
  – AN1292 Sensorless Field Oriented Control (FOC) for a Permanent Magnet Synchronous Motor (PMSM) Using a PLL Estimator and Field Weakening (FW) (DSDS01292A): ww1.microchip.com/downloads/en/AppNotes/01292A.pdf
  – AN908 Using the dsPIC30F for Vector Control of an ACIM (DS00908B): ww1.microchip.com/downloads/en/DeviceDoc/00908B.pdf

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